

Supernova Explosions inside Carbon-Oxygen Circumstellar Shells

S.I. Blinnikov^{1,2,3}, E.I. Sorokina^{2,3}

¹Institute for Theoretical and Experimental Physics, 117218 Moscow, Russia

²Sternberg Astronomical Institute, 119992 Moscow, Russia

³Max-Planck-Institut für Astrophysik, D-85740 Garching, Germany

Abstract

Motivated by a recent discovery of Supernova 2010gx and numerical results of Fryer et al. (2010), we simulate light curves for several type I supernova models, enshrouded by dense circumstellar shells, or “super-wind”, rich in carbon and oxygen and having no hydrogen. We demonstrate that the most luminous events like SN 2010gx can be explained by those models at moderate explosion energies $\sim (2 \div 3)$ foe if the total mass of SN ejecta and a shell is $\sim (3 \div 5) M_{\odot}$ and the radius of the shell is $\sim 10^{16}$ cm.

1 Introduction

Recently, Fryer et al. (2010) have presented arguments in favour of type Ia supernova (SN) explosions taking place within rather dense extended C–O envelopes formed during a merging process in Double Degenerate (DD) scenario. They obtained light curves which are very powerful in hard spectral range and last sometimes very long in visible light. On the other hand, there are observations of a very luminous type Ic SN 2010gx (Pastorello et al. 2010), and it was suggested that they may shine due to a shock wave propagating in C–O-rich circumstellar material.

Motivated by these results we construct light curves for several non-evolutionary type I supernova models which have dense C–O shells or winds around them.

2 Presupernova models

We have not tried to compute evolutionary or hydrodynamic models leading to formation of structures discussed by Fryer et al. (2010). All our presupernova models are constructed artificially as described elsewhere (Chugai et al. 2004; Baklanov et al. 2005). Their main parameters are given in Table 1. The interior part is a quasipolytropic model in mechanical equilibrium where temperature is related to density as $T \propto \rho^{0.31}$. This part has mass M_{ej} and radius R_{ej} , the subscript “ej” denotes here that this part becomes a supernova ejecta after explosion. In case of type Ib/c SN simulations M_{ej} can be much less than the total mass of the collapsing core and the condition of mechanical equilibrium is not necessary, it is just a convenient form of parameterization of models. The outer parts have power-law tails, $\rho \propto r^{-p}$, with p given in the Table 1. M_{Ni} denotes the mass of radioactive ^{56}Ni in ejecta, and M_{w} , R_{w} are mass and radius of the “wind”. No attempt is done to keep equilibrium in the “wind”, but the dynamical times of those huge envelopes are so large that no appreciable motion has developed during the time of light curve simulation.

The first set of models tries to mimic what is described (though very tersely) in Fryer et al. (2010). Fryer et al. (2010) claim that a double degenerate (DD) merger event leads to a density profile like $\rho \propto r^{-4}$ which is shown in their Fig. 5, as well as a $\rho \propto r^{-3}$ variant. However, this structure extends only up to $r \sim 3R_{\odot}$ there, while they see shock interaction up to $r \sim 10^{16}\text{cm} \sim 10^5 R_{\odot}$ in their Fig. 10 (Fryer et al. 2010). It is hard to imagine the formation of such an extended structure on a dynamical time-scale of DD event. Nevertheless, it is interesting to consider those extended structures independently of DD scenario because they can help to explain extremely powerful supernovae like SN 2010gx (Pastorello et al. 2010). We say a few words on other feasible ways to formation of these dense circumstellar shells in Sec. 5.

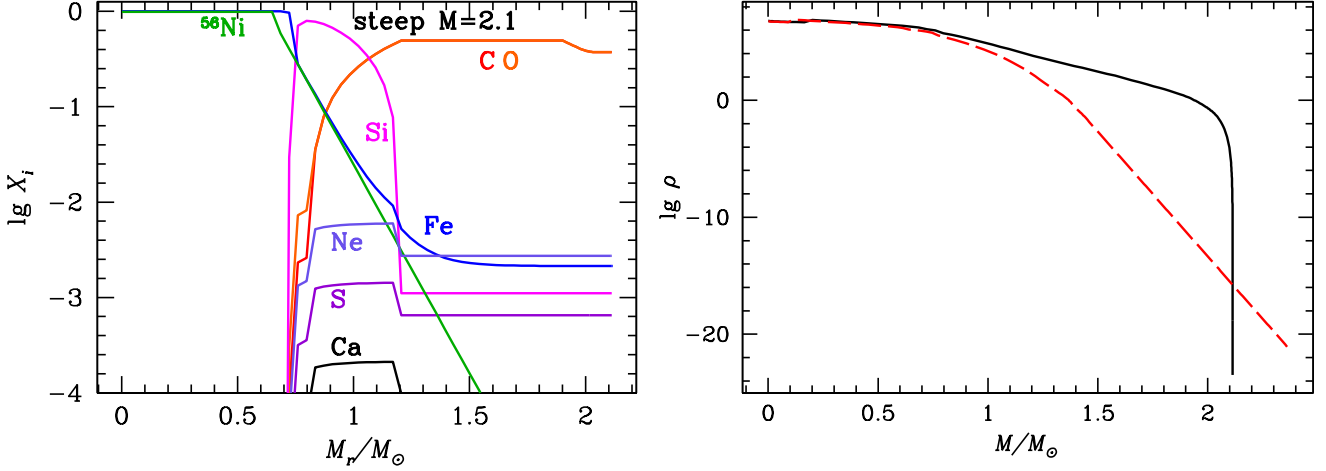


Fig. 1: Left: typical composition of “Ia” models used in simulations. “Fe” includes “Ni” (which is not only ^{56}Ni) and other iron peak elements. “C” and “O” lines almost coincide. Right: density profiles as a function of M_r for **steepIa** ($\rho \propto r^{-4}$; solid) and **medium bigIa** ($\rho \propto r^{-3}$; dashed) models.

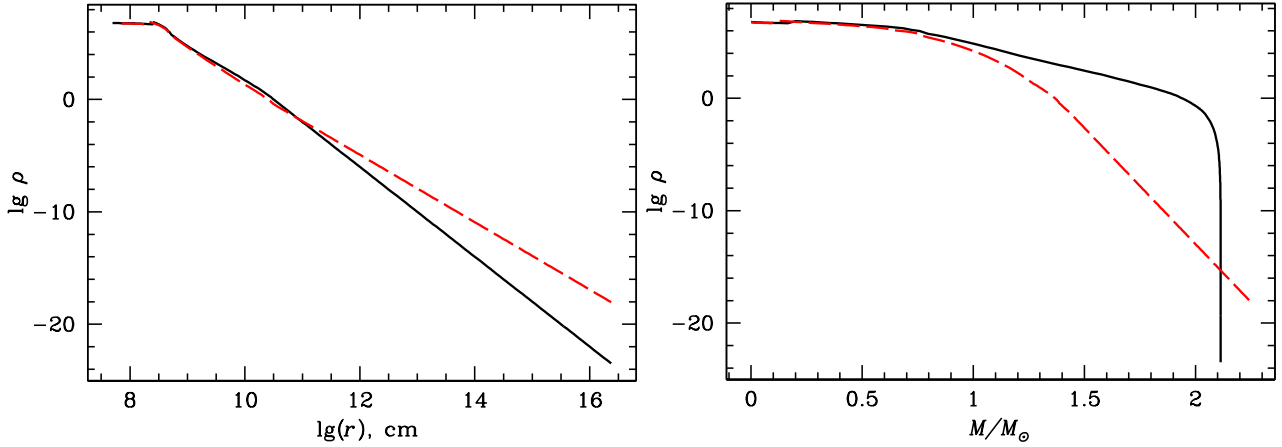


Fig. 2: Left: density profiles as a function of r for **steepIa** (solid) and **mediumIa** (dashed) models. (Model **medium bigIa** has the same structure of the “wind” like the latter, $\rho \propto r^{-3}$, but its outer radius is larger, $R_w = 3 \cdot 10^6 R_\odot$). Right: density profiles as a function of M_r for the same models.

We have two types of distribution of chemical composition in our simulations. A typical composition of the the first type is shown in Fig. 1. It tries to mimic a distribution of elements which can be produced in a thermonuclear explosion like in SN Ia. The models with this composition have a suffix “Ia” in their names.

The second type, “Ib”, has just a uniform distribution of elements in C–O envelope like in outermost layers of “Ia” model (in left panel of Fig. 1).

Density profiles for models with the “wind” $\rho(r) \propto r^{-4}$ and $\rho(r) \propto r^{-3}$ are shown in Fig. 1. All models, except for **medium bigIa**, have $T = 10^3$ K in the “wind”, and **medium bigIa** has $T = 2.5 \cdot 10^3$ K there. Already at $T = 2.5 \cdot 10^3$ K we have got a spurious flash of light emitted by the huge envelope.

3 Light curve simulations

We perform calculations of the synthetic light curves using our multi-group radiation hydrodynamic code STELLA in its standard setup (Blinnikov et al. 1998; Blinnikov & Sorokina 2004; Baklanov et al. 2005; Blinnikov et al. 2006).

The explosions have been simulated for all “Ia” variants by a “thermal bomb” with energy $1.6 \cdot 10^{51}$ ergs =

Table 1: Models (all masses M and radii R are in solar units)

Model	M_{ej}	R_{ej}	M_{Ni}	p	M_{w}	R_{w}	E , foe
steepIa	2	1	0.7	4	0.1	$3 \cdot 10^5$	1.6
medium bigIa	1.4	1	0.7	3	0.9	$3 \cdot 10^6$	1.6
mediumIa	1.4	1	0.7	3	0.8	$3 \cdot 10^5$	1.6
shallowIb	1	10	0	2.5	2.9	10^5	3
standardIb	0.2	10	0	2	3.5	$8 \cdot 10^4$	3
brightIb	0.2	10	0	1.8	4.8	$9 \cdot 10^4$	1, 2, 4

1.6 foe like in Fryer et al. (2010). A similar “thermal bomb” was used for “Ib” runs (the burst duration is 10 seconds in the innermost layers of ejecta, $\Delta M = 0.06 M_{\odot}$) with variable energy E , see Table 1. In radiation hydrodynamics runs we used 200 (100 in the ejecta plus 100 in the “wind”) radial mesh zones for “Ia” runs and 300 ones (150 plus 150) in “Ib” runs. All runs employed 100 frequency group in transport solver and relatively short spectral line list ($\sim 1.5 \cdot 10^5$) in the opacity routine.

4 Results

We report the numerical results for a set of selected models below.

4.1 Type Ia explosions within C–O shells

The light curves for “Ia” runs are shown in Figs. 3–5.

The main effect which is clearly visible is the dependence of the flux and duration of the light curve on the outer radius in the **mediumIa** (i.e. $\rho(r) \propto r^{-3}$) models. A physical explanation for this may be a longer diffusion time in the larger model. However, we should investigate also the dependence of the results on grid resolution. The presented “Ia” runs are done on grids with 200 radial by 100 frequency mesh points. We have checked them on cruder grids (90 radial by 100 frequency meshes). The behavior near maximum does not change much, while the tail part is more sensitive to the grid.

A direct comparison of our results with those of Fryer et al. (2010) is not possible, because we do not know their exact initial conditions. Our **mediumIa** models ($\rho(r) \propto r^{-3}$ envelopes) have about twice as much C–O as in Fryer et al. (2010) to exaggerate the effect of the circumstellar matter. Still for a smaller outer radius of the wind our light curves seem to evolve faster than in Fryer et al. (2010).

One should also note that in Fig. 4 we see initial “plateau” due to relatively high initial $T = 2.5 \cdot 10^3$ K in the “wind”. The radiation energy stored there is simply emitted away. The process of formation of the extended structure may be much longer than the time of its cooling. It seems that at least part of the early light in Fig. 9 of Fryer et al. (2010) may be attributed to this spurious emission.

4.2 Type Ib explosions within C–O shells

Supernova SN 2010gx (Pastorello et al. 2010) is extremely luminous and extremely interesting. For other very luminous events (Ofek et al. 2007; Smith et al. 2007, 2010; Gal-Yam et al. 2009; Young et al. 2010) some models involve explosions on a hypernova scale, where a huge amount of ^{56}Ni is produced (see, e.g., Nomoto et al. 2007; Moriya et al. 2010, for type IIn SN 2006gy and type Ic SN 2007bi).

Our goal is to explain SN 2010gx on another way, with minimum energy of explosion. This seems to be possible based on the old idea due to Grasberg & Nadyozhin (1986): when we have two subsequent explosion events. The first explosion is weak and produces the dense circumstellar structure (which we call “wind” here, but which is not a steady wind, of course). The second, normal SN explosion, produces very bright light due to the shock embedded into a dense medium. A physical mechanism for those multiple explosions, proposed by Heger & Woosley (2002) (pulsation pair instability) was used by Woosley et al. (2007) to explain SN 2006gy with moderate energy of ~ 3 foe without any radioactive material. One should keep in mind that there may be other, still unexplored, routes to repeated explosions in stellar evolution, especially in binary systems.

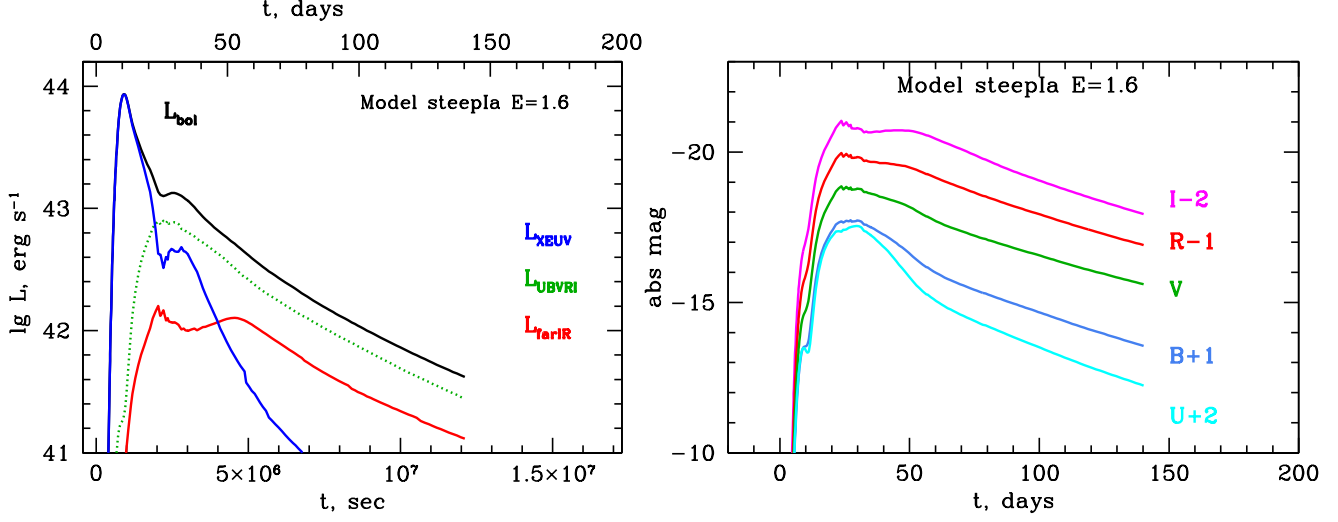


Fig. 3: Light curves of the model *steepIa* with $\rho(r) \propto r^{-4}$ in outer layers.

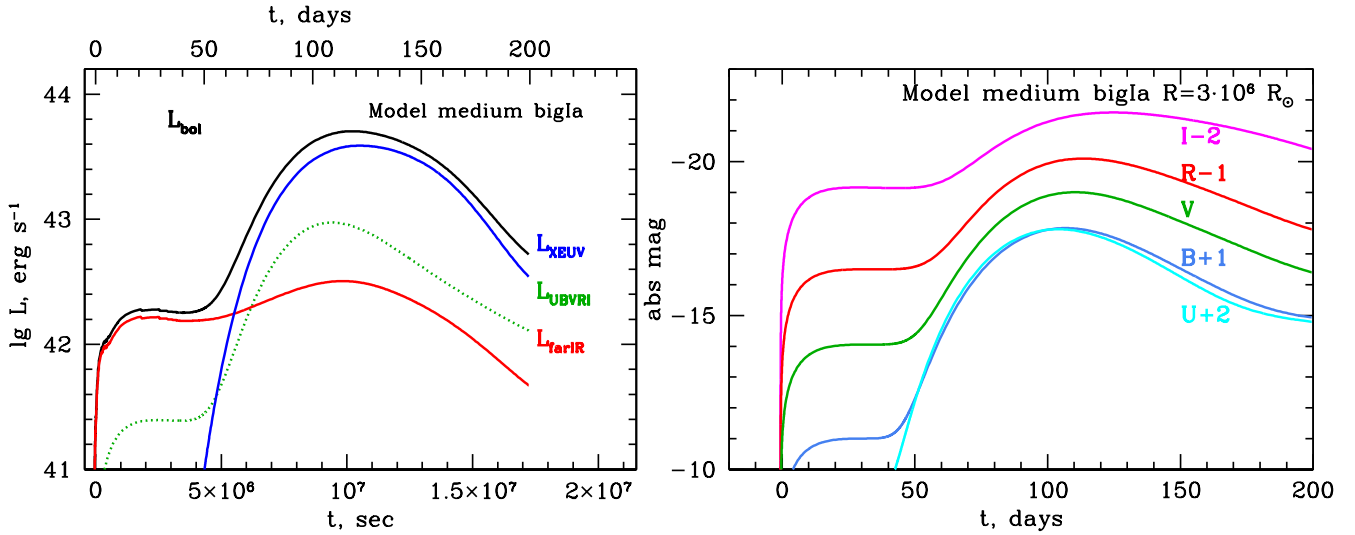


Fig. 4: Light curves of the model *medium bigIa* with $\rho(r) \propto r^{-3}$ in outer layers with a larger outer cut of the wind ($R = 3 \cdot 10^6 R_{\odot}$).

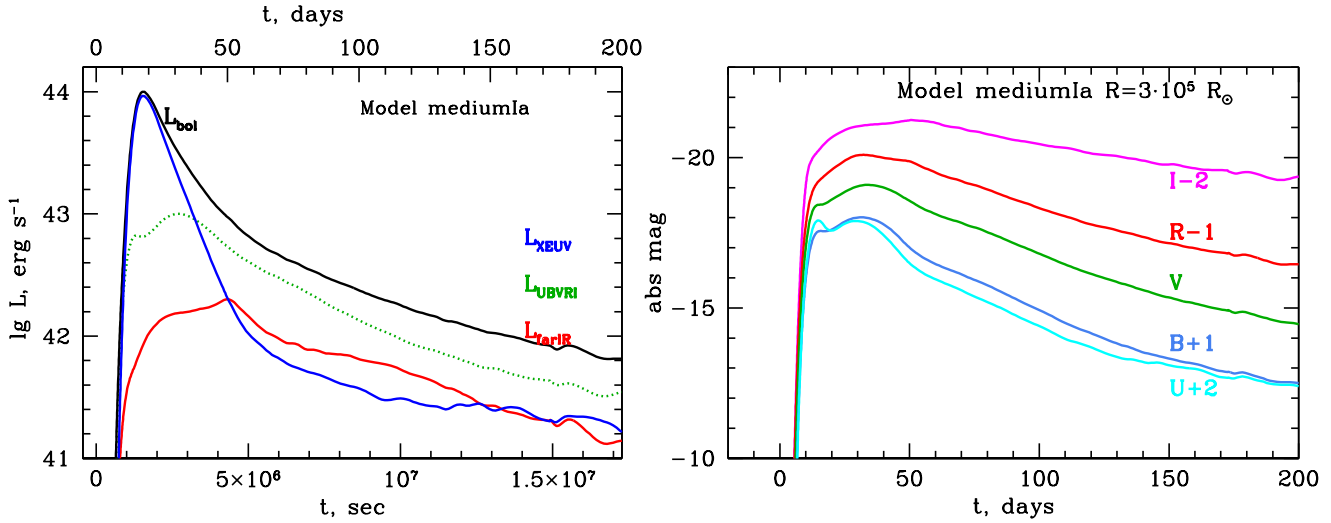


Fig. 5: Light curves of the model `mediumIa` with $\rho(r) \propto r^{-3}$ in outer layers and a smaller outer cut of the wind ($R = 3 \cdot 10^5 R_{\odot}$).

It is interesting to look at the results of our “Ib” runs with *zero* ^{56}Ni mass, where one can see a pure effect of radiative shock in C–O envelope producing a very bright supernova.

One clearly needs a very large radius to produce a bright event. The radius should not be too large, otherwise the diffusion of photons is too slow and the light curve becomes too wide. One needs high density for strong production of visible light by the shock, but not too high, otherwise the mass of the “wind” and the optical depth of the shell become too large.

We have run tens of different models, varying all parameters. Here we show only a small part of our results, see Figs. 6–7. Note, that the scale for the luminosity L has changed in comparison to Figs. 3–5. The values of $p = 4$ and $p = 3$ in the $\rho(r) \propto r^{-p}$ distribution produce too steep density gradients for our goal and we try smaller values of p . The models denoted `shallowIb` have $p = 2.5$. We call models `standardIb` if they have $p = 2$ because this is a standard value for a steady stellar wind, not for our set of models. The best value we find is $p = 1.8$ in the `brightIb` set.

There is an indirect evidence that the density profiles around supernovae having strong circumstellar interaction may be shallow indeed (Prieto et al. 2007), or do have rather complicated structure due to pre-supernova evolution (Dwarkadas et al. 2010).

4.3 Comparison with SN 2010gx. Role of opacity

Our code `STELLA` allows us to produce the light curve in different filter systems. Here we present them in SDSS *ugri* filters using the same standards and transmission functions as we did in Phillips et al. (2007). Following Pastorello et al. (2010) we assume redshift $z = 0.23$ for SN 2010gx. However, we take the distance modulus=40.28 which we find for this redshift in standard cosmology with $H_0 = 71$ km/s/Mpc, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$. Pastorello et al. (2010) do not give the distance modulus explicitly. We can guess that they assume a larger distance, because they compare the values of observed and absolute g magnitudes for the host galaxy. The larger distance can be obtained in a flat universe only for very low H_0 and Ω_m , perhaps excluded by current observational data.

Fig. 8 shows that our models `brightIb` easily reach observed maximum fluxes in g filters for various values of explosion energy. Energy $E = 2$ foe is perhaps too low, energy $E = 4$ foe is a bit too high, and the decay of light is too fast. The fluxes in *uri* filters are a bit lower than in observations, but before twiddling around those models we should note a very important factor, namely, line opacity.

In our standard `STELLA` setup we treat expansion opacity in lines as for type Ia supernovae, where we have homologous expansion and isotropic velocity gradient $dv/dr = 1/t$, with t time elapsed after the explosion. Now we have $dv/dr \gg 1/t$, because the light is produced in the radiative shock attached to a very dense shell (see Sec. 4.4 below). To check the effect of line opacity we have run several tests when the expansion

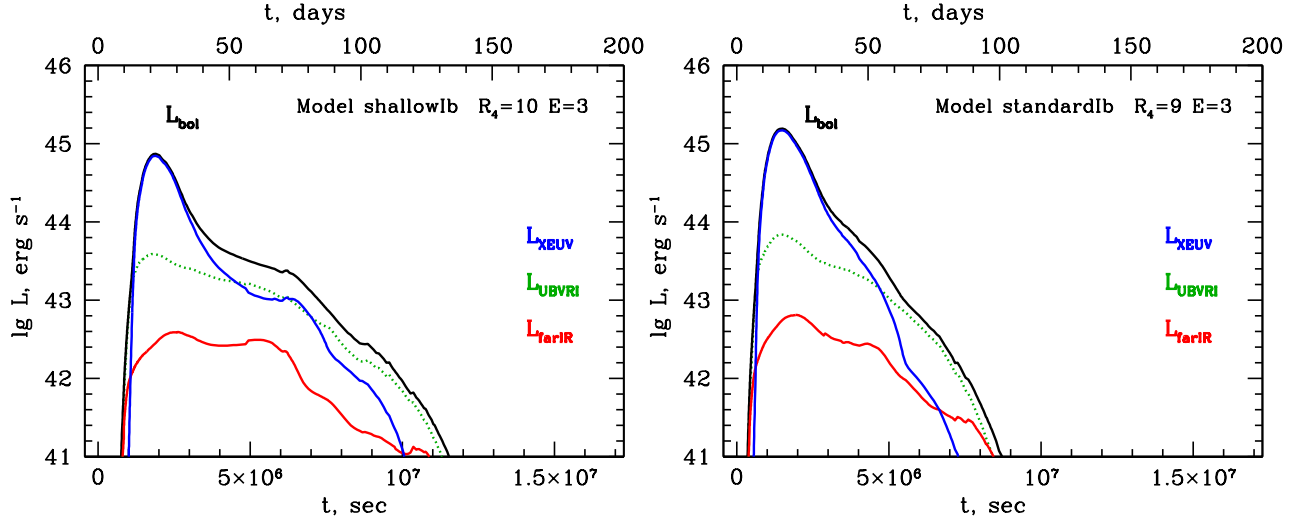


Fig. 6: Light curves of the models shallowIb and standardIb.

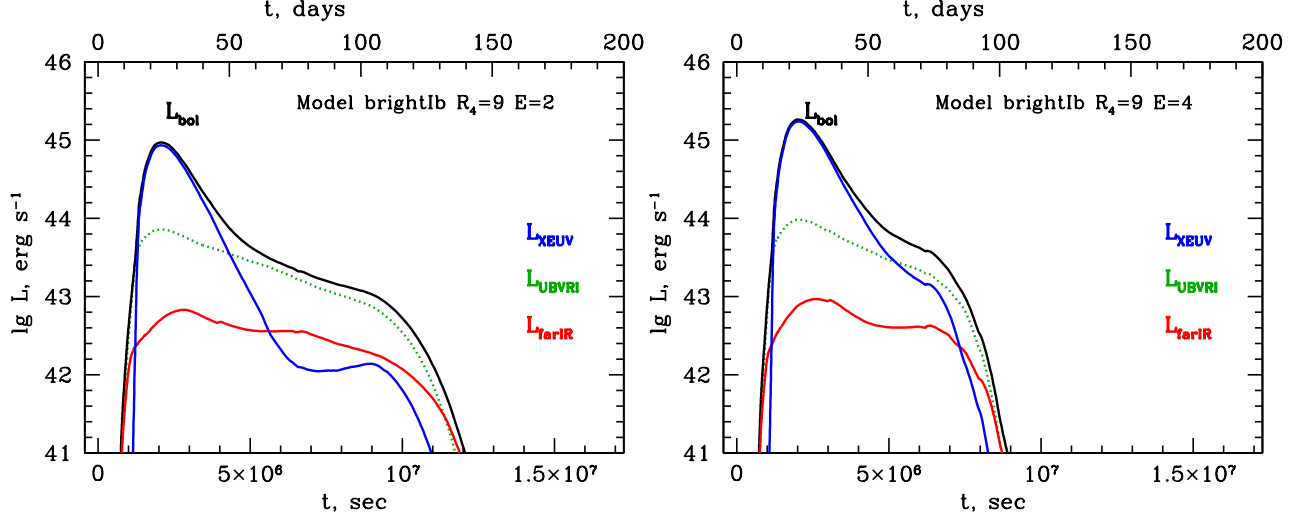


Fig. 7: Light curves of models brightIb with energies $E = 2$ foe (left) and $E = 4$ foe (right).

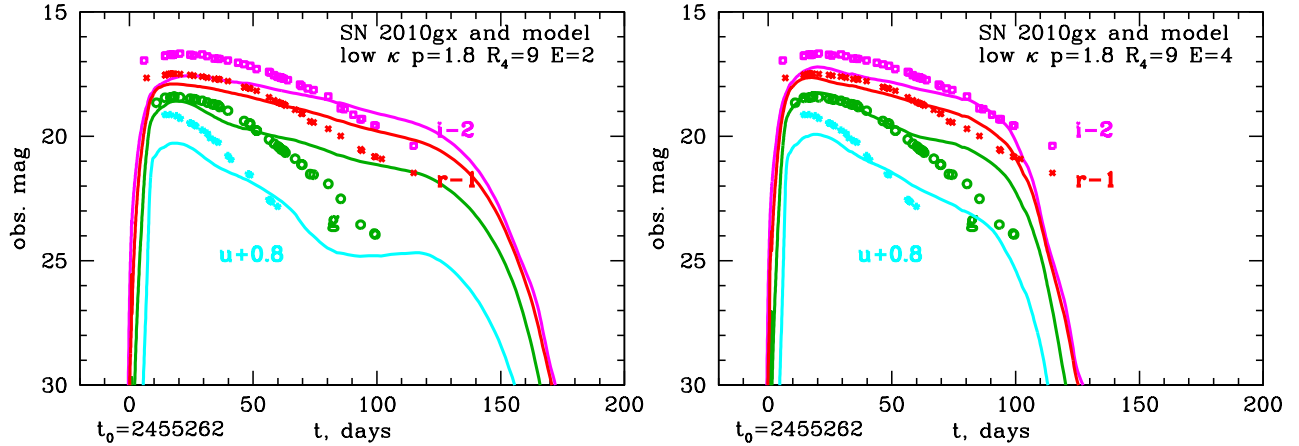


Fig. 8: Observed and synthetic light curves in *ugri* filters of models brightIb with energies $E = 2$ foe (left) and $E = 4$ foe (right).

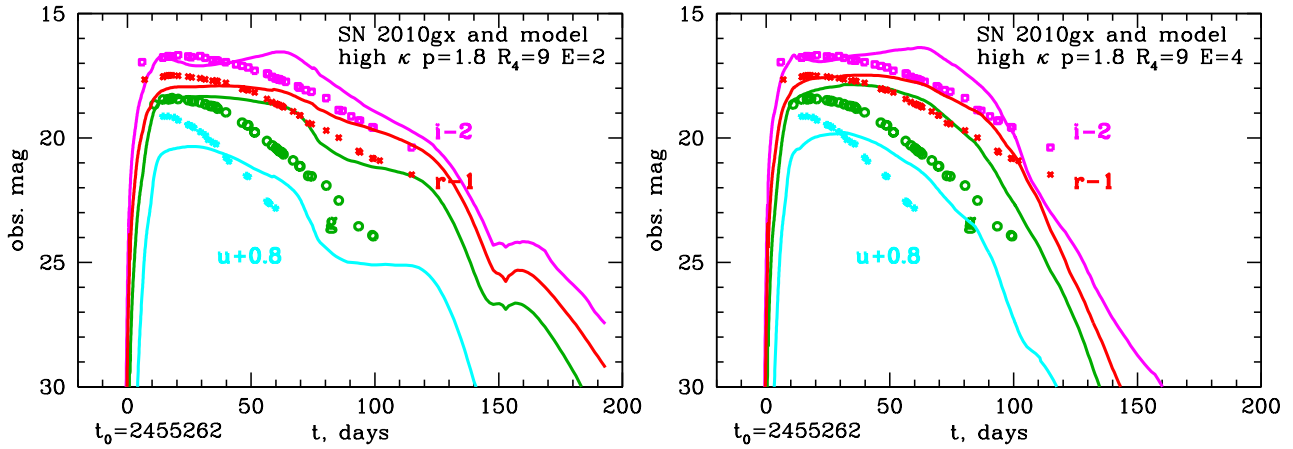


Fig. 9: Observed and synthetic light curves in *ugri* filters of models **brightIb** with energies $E = 2$ foe (left) and $E = 4$ foe (right) for higher expansion effect in line opacity.

opacity is calculated with the fixed value $dv/dr = 1 \text{ day}^{-1}$. Fig. 9 shows that in this case the observed flux is higher in many bands.

4.4 Hydrodynamic profiles of different models

We present in Fig. 10 a comparison of details in distributions of density, temperature, velocity, luminosity and Rosseland optical depth in models **steepIa** and **mediumIa** for the same date a few weeks after the explosion.

We see that a shock wave in the **steepIa** model is much stronger (due to a steeper density gradient) and leaves the grid quickly. The luminosity is due partly to heat release from the shocked matter and partly to ^{56}Ni , but not to the shock itself: for the epoch shown in Fig. 10 the shock has already left the grid. Note that units of velocity on the plot are 10^9 cm/s , i.e. ten thousand km/s. For a shallower profile $\rho(r) \propto r^{-3}$ the shock is “buried” deep and forms a dense shell like in our SN IIn models (Chugai et al. 2004; Woosley et al. 2007). One can see that the shock associated with this dense shell is contributing to luminosity (although the ^{56}Ni role is not negligible). It is interesting to study models with zero mass of ^{56}Ni (as in Woosley et al. (2007)) and we do this for SN 2010gx.

We do not observe a box-like profile of temperature as in Fig.10 of Fryer et al. (2010).

Fig.11 shows profiles for one of our models of SN 2010gx. We see a formation of very dens shell and luminosity production on the shock.

5 Summary and discussions

The aim of the current work was to check numerically the role of shock interaction in producing light by shocks in carbon-oxygen “winds” around type I supernovae. The problem arises from observations (Pastorello et al. 2010, and references therein), as well as from theory (Fryer et al. 2010). Our main conclusion is that the shock interaction is very important indeed and it cannot be ignored in many cases.

We do not know exact initial conditions used by Fryer et al. (2010), and we do not confirm their conclusion on long-living shocks in steep ($\rho(r) \propto r^{-4}$) density profiles. We suspect that the shock lives there due to another distribution of matter (there is perhaps a medium with $\rho(r) = \text{const}$ on their grid). In part of our results we see initial flashes of light due to initial temperature in the “wind”, even if it is as low as 2500 K. Nevertheless, we find long-living radiating shocks in all profiles with $\rho(r) \propto r^{-3}$ and in the less steep ones.

A big question remains on the mechanism of the formation of those huge and dense envelopes. What is the time-scale of this process? How far can the envelope extend in radius? What is the density profile and the temperature of matter before the core explodes?

If those structures form in reality then we can have extremely bright and long light curves. This question deserves further investigation. The effect of the extended envelopes is probably more important not for SNe Ia

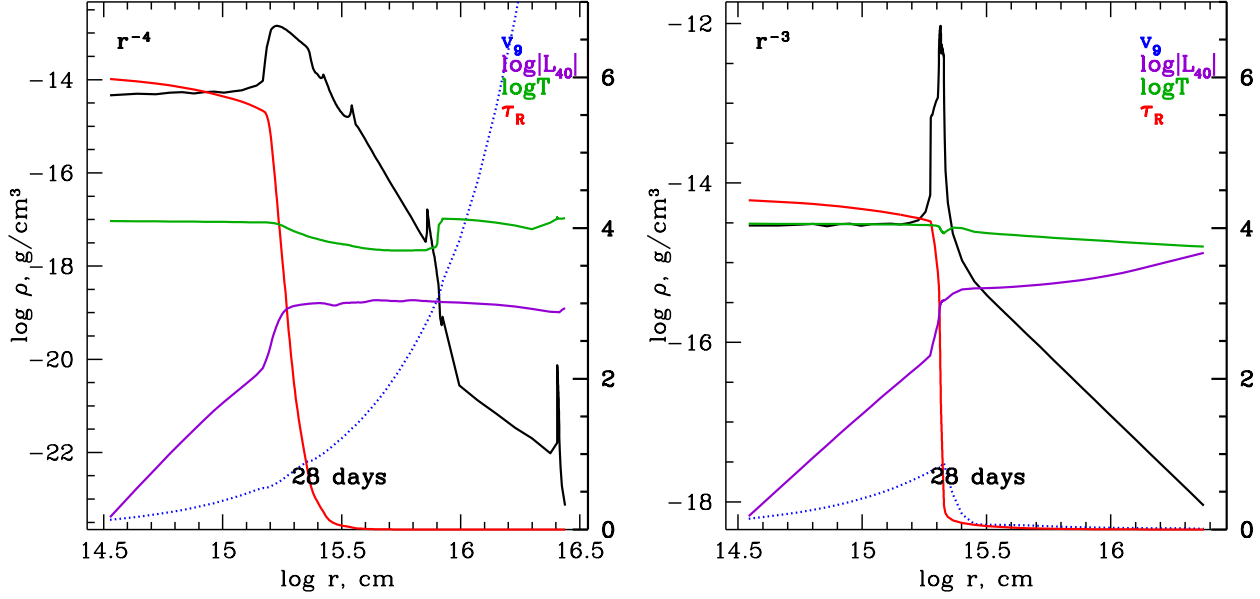


Fig. 10: Profiles of density (black lines), velocity (in 10^9 cm/s, blue), luminosity (logarithm of absolute value in 10^{40} ergs/s, violet), logarithm of matter temperature (green) and Rosseland optical depth (red). The scale for density is on the right Y axis, for all other quantities it is on the left Y axis. Left panel: model **steepIa** with $\rho(r) \propto r^{-4}$ in outer layers. Right panel: model **mediumIa** with $\rho(r) \propto r^{-3}$ in outer layers

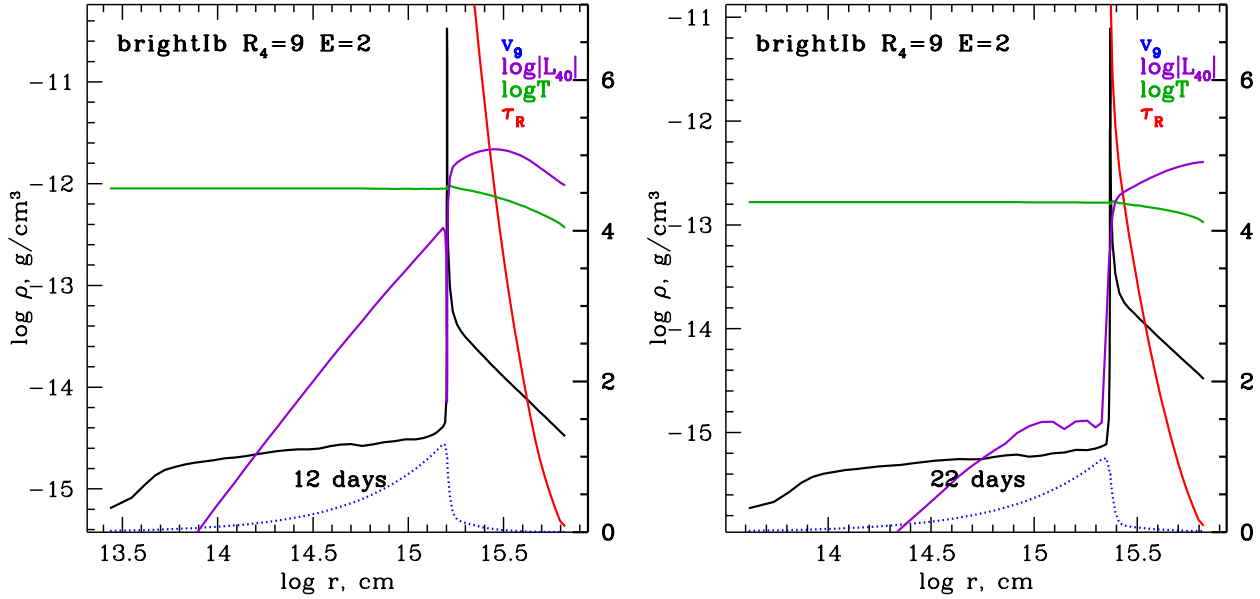


Fig. 11: The same as in Fig. 10, but for the model **brightIb** with $\rho(r) \propto r^{-1.8}$ in outer layers and $E = 2$ foe. Left panel: at day 12. Right panel: at day 22.

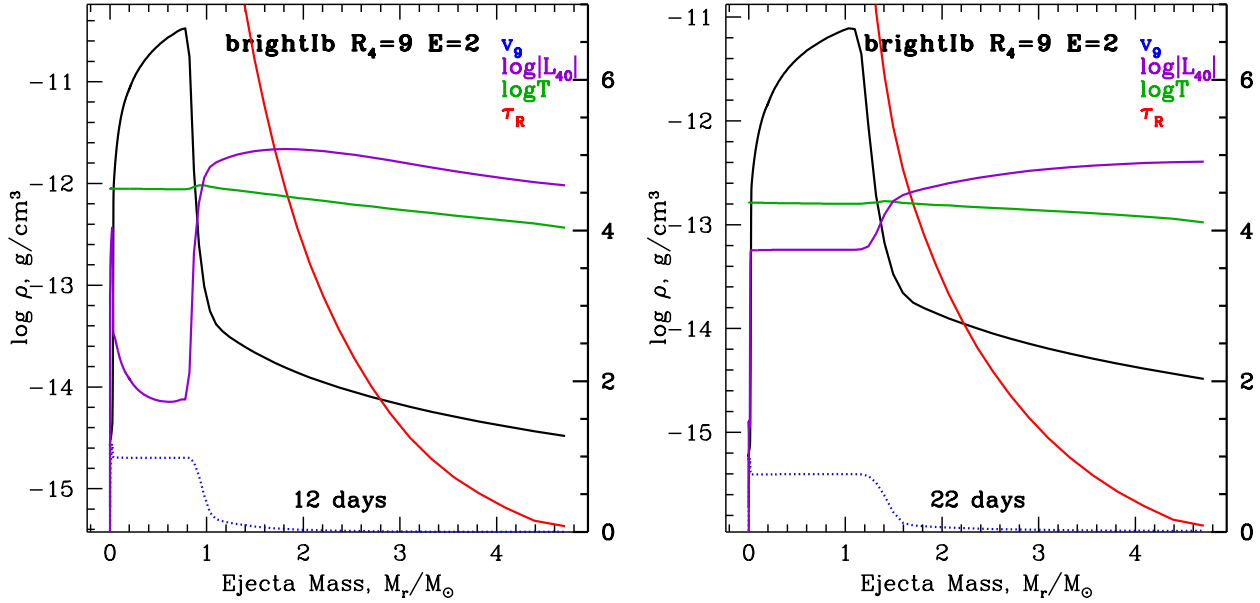


Fig. 12: The same as in Fig. 11, but as a function of M_r . Left: at day 12. Right: at day 22.

but for very luminous SNe Ib/c discovered recently (Pastorello et al. 2010). In that case one may think about pulsational pair instability as a means for formation of extended shell. One can also speculate about mergers of white dwarfs with CO-cores of WR stars. The merger event may lead to a moderate explosion with energy of a few percent of foe which forms a cloud of matter around the presupernova expanding with relatively low velocity. Then, if the core collapse follows within *years* after the merger, one can have all needed conditions for very bright supernovae.

Our simulations show that the very luminous SN 2010gx may indeed be produced by a supernova explosion if there is enough surrounding material for a shock to transform the kinetic energy of ejecta into observed light. We find that SN 2010gx can be explained at explosion energies $\sim (2 \div 3)$ foe for a non-steep density profile, if the total mass of SN ejecta and a shell is $\sim (3 \div 5) M_\odot$ and the radius of the shell is $\sim 10^{16}$ cm.

The fits to fluxes in individual filters are not yet perfect in our simulations. This is natural: we have taken quite arbitrary and primitive chemical compositions, density distributions, etc. But in many cases the synthetic fluxes are *higher* than observations, and this looks encouraging. One can try building a better fit to observations by variations of initial conditions in the model. However, it seems that it is too early to optimize the models along these lines. This optimization will probably not give us a true insight and a better understanding of the problem.

E.g., many technical subtleties still remain in the treatment of line opacity. First, we should correct for the expansion effect not only the flux equation, but also the energy equation. Microscopically, for exact monochromatic opacity, there is no expansion effect (Blinnikov 1996, 1997). For average absorption opacity there is some effect, but it can not be treated so simply as by Hoefflich et al. (1993), (see Sorokina & Blinnikov 2002). Moreover, there is another complication with anisotropic velocity gradient. Thus, before optimizing the fits, one has to build new techniques for radiation transfer in these conditions.

We have not discussed observed line spectra: for type II_n, by definition, one clearly sees narrow emission lines produced in the shells. Not so in SN 2010gx: narrow circumstellar lines are not seen (Pastorello et al. 2010). There is no hydrogen, which is easily excited, and the most abundant elements, carbon and oxygen, should be present perhaps as C II and O II ions in the envelope (see the temperature in Figs. 11,12). These ions do not have many strong lines in visible light. It is not easy to identify C and O lines on photospheric stage in SNe Ic (Young et al. 2010), and now they should be excited even if there is no radioactive material. So one has to look for *weak and narrow* lines in noisy spectra. This problem certainly deserves further investigation with account of different conditions for ionization/excitation of shells under the shock radiation.

The main complication to the whole picture is possible fragmentation of the dense shell. The attempts

on multi-D treatment of SN ejecta evolution are rather old (Tenorio-Tagle et al. 1991; Chevalier & Blondin 1995; Blondin et al. 1996), more recent results and references may be found in (Dwarkadas 2007, 2008). See also van Marle et al. (2010) for the case of SN 2006gy, but without real treatment of radiative transfer. There are several 3-D MC transport codes (Hoeftlich 2002; Lucy 2005; Kasen et al. 2006, 2007; Sim 2007; Tanaka et al. 2008; Kromer & Sim 2009) but they are not actually coupled to hydrodynamics and there are many difficulties in doing this (Almgren et al. 2010).

Full NLTE treatment is needed to predict spectra, but very little is done on this even for SN IIn. E.g., Dessart et al. (2009) are surprisingly successful in reproducing the spectra of SN 1994W in a set of atmospheric models, but their method is applicable only to monotonic velocity structures, not to shocked shells. Moreover, one should be cautioned about the relation of “photospheric” radius found by Dessart et al. (2009) which shrinks, and the radius of the shocked shell in SNe IIn which grows. This is already explained by Smith et al. (2008, 2010).

Nevertheless, we conclude that, provided the formation of rather dense and extended circumstellar shells, the extremely powerful events of type Ib/c like SN 2010gx can be explained with moderate energy of explosions without invoking any radioactive material.

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